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BIOENGINEERING PROBLEMS IN EARLY MANNED SPACE FLIGHT

By

Richard W. Lawton, Bertram J. Smith, Donald R. Ekberg

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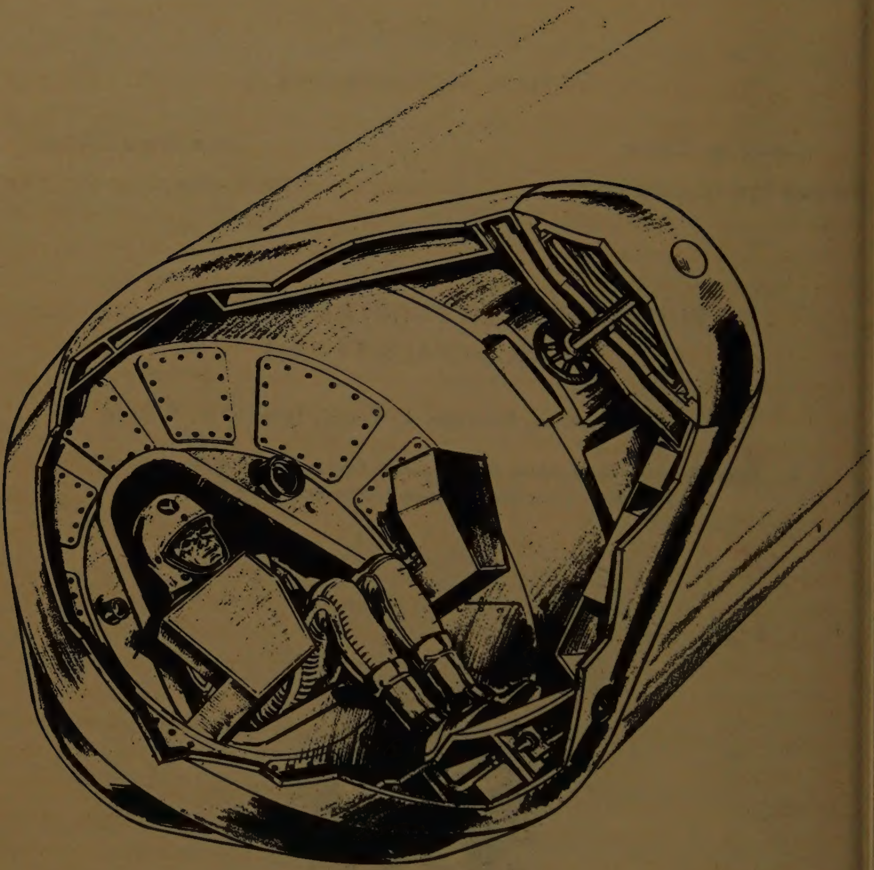

BIOENGINEERING PROBLEMS IN EARLY MANNED SPACE FLIGHT*

Richard W. Lawton, Bertram J. Smith, Donald R. Ekberg
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General Electric Company, Philadelphia, Pa.

In July 1958, the Missile and Space Vehicle Department of the General Electric Company, Philadelphia, Pa., undertook, under an Air Force contract, an intensive study and design effort relating to the problem of manned space flight. This effort, conducted in parallel with that of the North American Aviation Company, Los Angeles, Calif., culminated eighty days later in three preliminary designs and mock-ups. As a part of this intensive study a review of the relation of the biological, psychological, and medical disciplines necessary to the problem of manned space flight was undertaken, particularly with relation to the influence of these disciplines on the design criteria for the first manned space vehicle. This paper derives from the original Air Force report,[1] modified by omissions and elaborations resulting from a continuing study of the field.

No review can be expected to be complete, authoritative, or even timely in this rapidly developing area, although manned space flight is now approaching reality under the auspices of the National Aeronautics and Space Agency (NASA), Langley Field, Va., as Project Mercury.

This review is selective and directed toward the engineering solution of the manned space flight problem. The primary criterion for vehicle design is the safety of the pilot. In a close-working relationship, engineers, psychologists, physiologists, and physicians have sought to create an optimum solution to the safety problem. An optional solution consistent with the present state of the art, however, may not be entirely optional from the point of view of the engineer or from that of the other disciplines involved. It is determined by a process of give and take so that, in the end, the safety of the space pilot is assured. This review is concerned primarily with data pertinent to this compromise.

This review is restricted further by a number of boundary conditions. It is concerned primarily with the man-to- and the man-from-space problems. Long-term residence of man in space is not considered. Launching boosters with thrusts of 300,000 to 400,000 pounds are contemplated. The mission duration is taken as 24 hours or 16 to 17 orbits. Orbital altitudes up to only 200 miles are considered; therefore, radiation is not regarded as a significant problem. Orbit ejection occurs upon firing a fixed-charge rocket (retrorocket) that slows the vehicle and begins its descent. Only ballistic re-entry is considered. Pure drag vehicles as described here emphasize man's passive tolerance to acceleration, whereas lifting vehicles, such as the X-15 aircraft, stress man in the role of a controller under complex accelerations. The mission is terminated by parachute deployment, descent, and water impact.

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*The views expressed in this paper are those of the authors and do not necessarily express the opinions of either the United States Air Force or the National Aeronautics and Space Agency.

Finally, no effort has been made to present a complete bibliography. Only recent selected references are cited.[2-5] Attention is directed to Volume 4 of *Astronautics*, referred to elsewhere in this paper, for an up-to-date review of the field.

Acceleration

The problems of acceleration and deceleration are of prime importance in man's conquest of space. The acceleration climate covers a broad range, from a few milli-g in orbital flight to many times the force of gravity during launch, re-entry, and landing impact. An analysis of man's tolerance to acceleration loads is complicated by the possible simultaneous occurrence of spin, vibration, and oscillation of various magnitudes. Data for man relating to such combined accelerations are sparse as compared to data on simple continuous g loads.

Man's tolerance to acceleration depends upon a number of factors, including the magnitude of g, its duration and, probably, its rate of onset, as well as the relation of the body axis to the acceleration vector. Finally, human tolerance is defined by means of an end point. Under different circumstances the tolerance end point may be taken as loss of vision or unconsciousness, inability to breathe, intense pain, shock, or actual structural damage. A more sensitive and perhaps more pertinent end point is the capacity of man to perform given tasks under acceleration.

The physiologist discusses acceleration in terms of man's sensations. He thinks of the seated man on earth, for example, as being forced down into his chair rather than of the chair as acting to support the man. He calls this *positive* acceleration. If the acceleration acts through the long axis of the body of the seated man, the principal effects relate to the hydraulic disturbance in the vascular system. This disturbance is manifested by visual impairment and finally by unconsciousness.

A man standing on his head is said to be subjected to one *negative* g. Accelerations transverse to the long axis of the body are called *transverse* g and side-to-side accelerations, *lateral* g. In transverse and lateral g no significant hydraulic disturbances are produced. For high transverse acceleration, pain and inability to breathe serve as tolerance end points. Short acceleration pulses or impacts do not produce hydraulic effects. For high g impacts, either shocklike states or actual structural damage may be produced.

Tolerance to negative acceleration is most limited with respect to aximum g level and time. The highest g levels attained by man are ssociated with the transverse position. Tolerance to positive accelera- ion falls between these two. Because of the respiratory difficulty and ain associated with high transverse g, the physiologist has studied the ffects of partial supination or partial pronation. He seeks to thread his vay between the pain and discomfort of transverse g and the lower accel- ration tolerance of positive g. By means of such devices and procedures s leg elevation and flexion, a g suit, special breathing methods, and ven the partial molding of the support structure to the man, he seeks to naintain functional integrity and to diminish pain and discomfort at high levels. It is fortunate that elevation and flexion of the legs in the trans- erse position are associated with an increase in g tolerance, because he diameter of the first space capsule will be limited. While angulation llows fitting the man into relatively small space capsules, this restricted osition is probably unacceptable for long periods in orbit.

It is generally agreed that the most suitable position for man is a upine one. The prone position is associated with considerable facial iscomfort and the requirement for an awkward restraint system. If it is equired that man be subjected only to supine transverse g during both aunch and re-entry phases of the flight, it is apparent that either (1) the an must be turned over between launch and re-entry, (2) the vehicle ust be turned over, or (3) the vehicle must be launched backward by eans of a low-drag fairing or cover arrangement. The thrust of retro- ocket firing, however, must be taken on the restraint harness rather than he seat.

Launch acceleration. The nominal launch acceleration patterns of the oosters contemplated for manned space flight are entirely within the cceleration tolerance of man in the supine position. However, questions emain with respect to the effects on man of rapid booster burn-out. At urn-out the man will be subjected to a deceleration step function from he terminal acceleration value to zero g. Such a deceleration step func- ion probably cannot be simulated and studied on earth. It is not believed hat this event will result in any marked physiological or mechanical isturbance, but some concern has been expressed as a result of an xperiment by von Beck[6] in which a rapid transition from high g to weight- essness was achieved during Keplerian flights with jet aircraft. It was bserved that a disorienting experience occurred upon entering weight- essness from a high g maneuver. This disorientation did not occur when eightlessness was preceded by a low g pull-up.

Perhaps more important than the nominal launch acceleration pattern is hat associated with the launch pad and boost emergency escape. The cceleration patterns associated with escape under these circumstances vary in kind and severity. On the launch pad and during the first few seconds of boost, thrust must be provided to separate the manned capsule from the propulsion system. However, because the whole escape event occurs within the atmosphere, the acceleration imparted by the escape rockets is followed by a rapid deceleration that must be taken on the straps or harness system. No human experimental data applicable to such a rapidly fluctuating g pattern of such large magnitude exists.

If failure to enter orbit were to occur because of booster failure, ballistic re-entry of the vehicle might be associated with as much as 20 to 25 g peak deceleration. Recent experiments[7] on the human centrifuge at the Naval Air Development Center, Johnsville, Pa. have shown that, under appropriate restraint conditions re-entry decelerations as high as 25 g may be tolerable, but only with a specially constructed molded couch for the man. This support system, developed by NASA, noticeably reduces pain, perhaps by providing good lateral support for the chest and abdomen and by preventing displacement of internal organs (FIGURE 1).

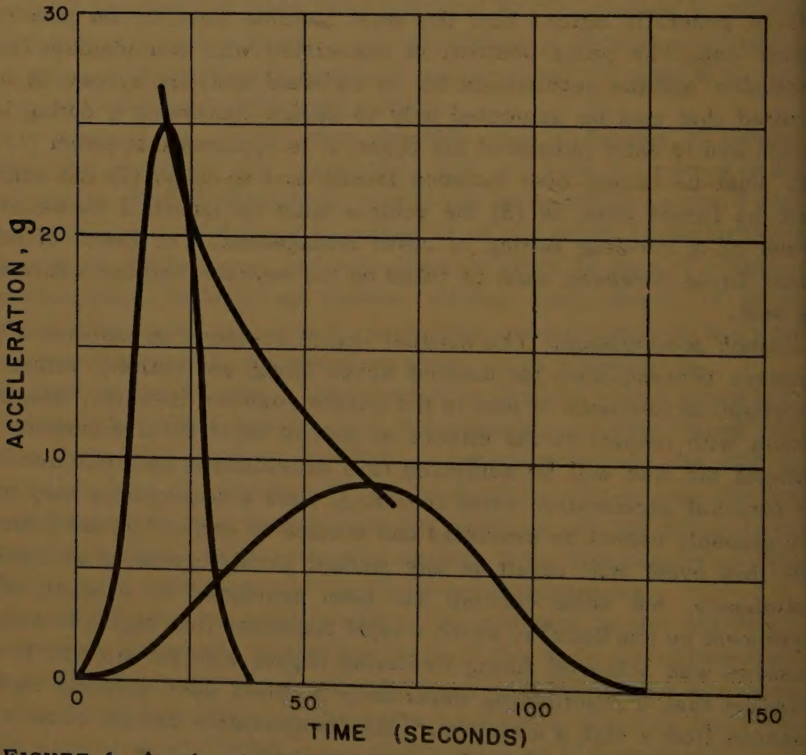


FIGURE 1. Acceleration tolerance data from human centrifuge, Naval Air Development Center, Johnsville, Pa., showing g-time curves of simulated re-entry accelerations tolerated by man. Peaks from 8 to 25 g. NASA molded restraint system. As peak g values increase, base time decreases and g-time area remains approximately constant.

Re-entry deceleration. The re-entry deceleration problem can be ap-roached best through a consideration of the relation between the decel-eration that will be imparted to the man and the factors that contribute to he dispersion and thus to the physical location of a space vehicle in the cean. Among the factors affecting such dispersion are the vehicle atti-ude at initiation of return, the orbital velocity at that time, and the path ngle at initiation of return. Other factors include the alignment and nagnitude of the retrorocket-imparted velocity vector, rocket firing, and enter of gravity offsets. The total dispersion will reflect all the toler-nces and uncertainties associated with the mechanics of ejection from rbit and in the ground-tracking system.

In a study by Galman and Grady[8] it was shown that the alignment angle f the retrorocket-imparted velocity vector is critical. For any particular mparted velocity, the range varies with the alignment angle β (FIGURE). For each velocity value there is an optimal value of β associated vith minimum range and dispersion. The selection of the value $\beta = 0$ imparted velocity vector directly opposite to the vehicle velocity vector) as the advantage of producing the lowest re-entry deceleration and per-aps of simplifying the attitude control system, but is associated with a arger range and dispersion. FIGURE 3 shows the relation between $\beta = 0$, $\beta_{opt.}$ and the range, imparted velocity, and the peak g. None of the g val-ies shown is outside man's acceleration tolerance in view of the recent xperiments at Johnsville, Pa. Because of the problems associated with ocation and recovery of a space vehicle after landing, one course of ction is to permit high g levels to occur so that dispersion may be imited.

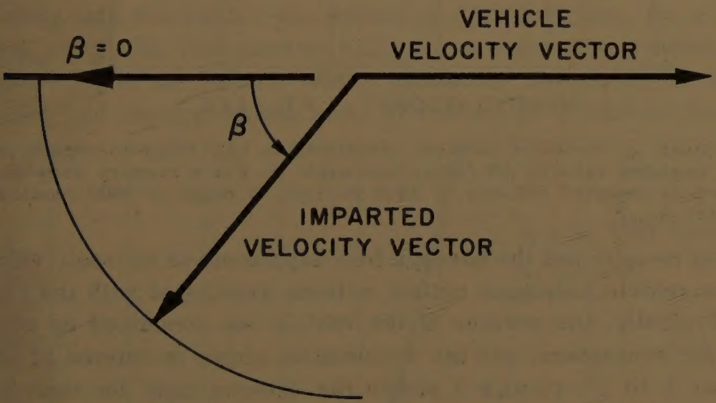


FIGURE 2. Definition[8] of imparted velocity angle β.

If higher g values are unacceptable, a variable area-drag device such s a hypersonic chute or drag brakes might be considered. These provide greater braking at higher altitudes and spread the deceleration over larger time span and reduce its peak value. While it is widely believe that human tolerance to acceleration is related simply to the area unde the g-time curve,[9] that is, equal areas are equally tolerable, the relatio may break down when more experience is obtained at the more extreme levels and when a variety of end points (pain, performance capability) i considered.

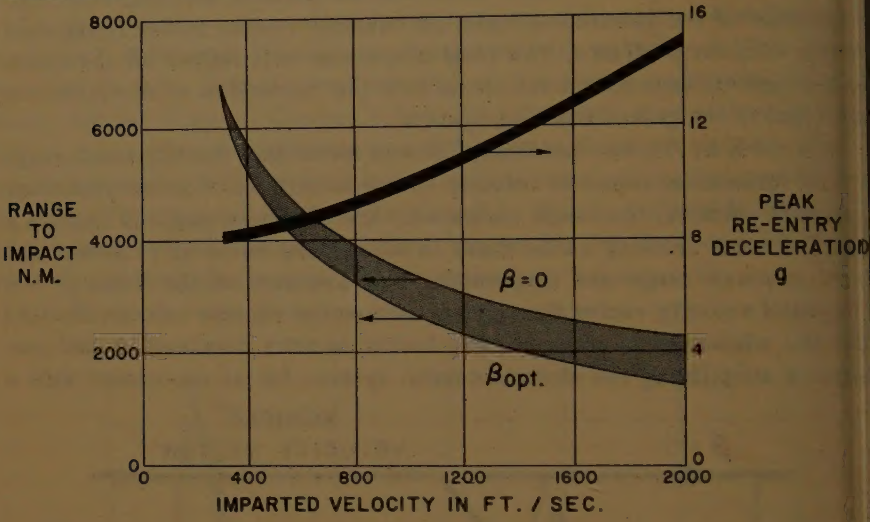


FIGURE 3. Relation between deceleration (g), range-to-impact (nautica miles), imparted velocity (ft./sec.) and angle β. For a re-entry deceleration o 12 g and an imparted velocity of 1400 ft./sec., a range of 2000 nautical mile occurs for β_{opt}.[8]

During re-entry and the passage from supersonic to subsonic velocities a space vehicle undergoes certain motions associated with the deceleration. Typically, the motions of the vehicle are conceived as stabilize above the atmosphere, and the deceleration phase is entered at an angl of about 1 to 2°. TABLE I shows the extreme case for three re-entr vehicle shapes entering at an angle of 10° because of failure of thi control system. Generally, the vehicles oscillate at varying frequencie and amplitudes. The frequencies increase to reach a peak coincident wit the peak axial deceleration and then decline, whereas the amplitude decrease continually during the deceleration. During and following th deceleration phase and before parachute opening the vehicle may at firs nutate and then tumble unless stabilized.

Inspection of the results of calculations suggests that oscillations o these magnitudes and frequencies in a g field are not damaging to th well-restrained man, providing he is positioned near the vehicle's cente of gravity. Currently, it is not possible to test this conclusion complete ecause of the poor response times of available centrifuges. For example, he Johnsville centrifuge is capable of ±1° at 1 cps at 12 g only if the ondola is balanced meticulously.

TABLE 1

COMPARISON OF RE-ENTRY DYNAMIC LOADS*

Configuration	A	B	C
eak axial acceleration ~ g	12.5	12.5	12.5
eak normal acceleration ~ g	0.40	0.25	0.56
eak oscillatory loads ~ g/ft.	0.12	0.10	0.06
eak oscillation frequency ~ cps	2.0	1.5	1.4
agnitude at this frequency ~ degrees	1.0	2.0	1.4

*Initial angle of attack, 10°

Re-entry at escape velocity. Before leaving the subject of re-entry, ome consideration should be given to re-entry at high velocities. FIG-RE 4 shows the relation between re-entry angle and peak deceleration or re-entry into the earth's atmosphere at 35,700 ft./sec. for a vehicle ith W/C_DA of 100. The quantity W/C_DA is a descriptive vehicle param-ter consisting of the vehicle weight divided by the product of the drag oefficient and the appropriate area. At these high velocities there is a

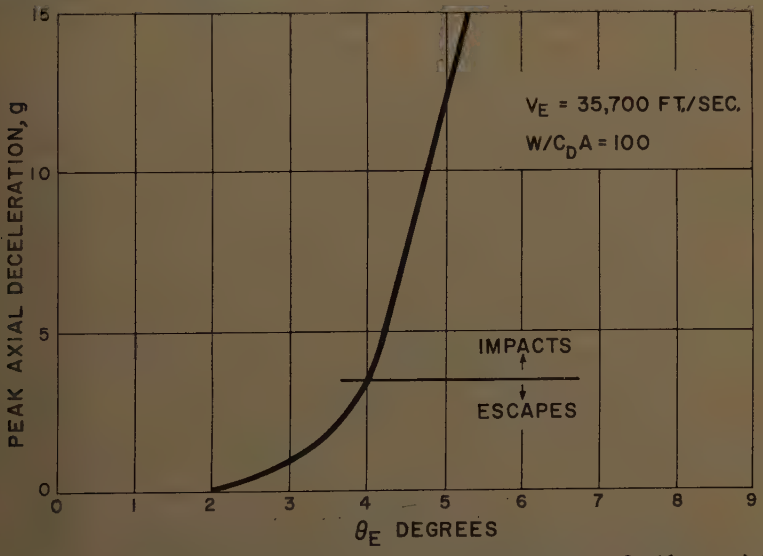


FIGURE 4. Peak axial deceleration (g) at re-entry angles θ_E (degrees) for a e-entry velocity of 35,700 ft./sec. and a vehicle with a W/C_DA of 100. Between and 5°, the g level increases from 4 to 12 g.

critical re-entry angle in order that the vehicle be captured. In the illustration this angle is about 3.9°. At lesser angles the vehicle is decele ated, but passes through the atmosphere into an elliptical path. The pea deceleration rises rapidly with an increase in the re-entry angle. If a pea deceleration limit of 12 g is arbitrarily imposed, the total range of permissible re-entry angles for capture is 1°. Thus, extraordinary precisio is required in this maneuver for a ballistic vehicle. A number of alternatives to the problem of re-entry precision has been suggested, notabl variable-lift or variable-drag vehicles and the application of counterthrus One solution involves immersion of the man in water. This procedure ha been demonstrated to extend man's transverse g tolerance to 32 g, th maximum capability of the centrifuge at Johnsville.[7] Water immersion, o course, is awkward, but perhaps this technique also might be considere in terms of radiation protection for the man and thus serve a doubl purpose.

Impact. The final phase of the acceleration profile during space flight is the landing impact on the earth. Controlled experimental impact data on the human are scarce because, in this type of research, people are subject to injury. Data must be drawn from a variety of sources, such as accidental free falls and airplane and automobile crashes. The source of good data on abrupt deceleration is Holloman Air Force Base.[10] Unfortunately, data at present are too scarce and are often compounded by variations in the restraint systems used. The exact shape of the deceleration-time pulse is difficult to control. The problems associated with the landing impact may be among the most critical to be faced in the first attempts at space flight. It seems probable that this problem will exist for some time to come: space missions of the future may always require rapid operational ballistic re-entry for escape or other purposes.

Recently a new method of expressing human impact data has been suggested by Kornhauser.[11] It has been observed empirically that when failure data from structural impact tests are displayed in terms of the velocity change versus the average acceleration, a curve characterized by two asymptotes is obtained. The horizontal asymptote is associated with high-g short-time pulses. The vertical asymptote is related to pulses of long duration. The establishment of these two asymptotes defines damage and nondamage zones. In FIGURE 5 such a curve has been fitted to human impact data accumulated from the literature. The asymptotes are at approximately a ΔV value of 80 ft./sec. and an average g value of about 20 g.

This type of presentation of impact data is under investigation, using mice in drop tests.[12] The form of the g-time curve is controlled by impacting on objects of various shapes and composition. In this way the effects of varying the rate of onset of the acceleration may be studied.

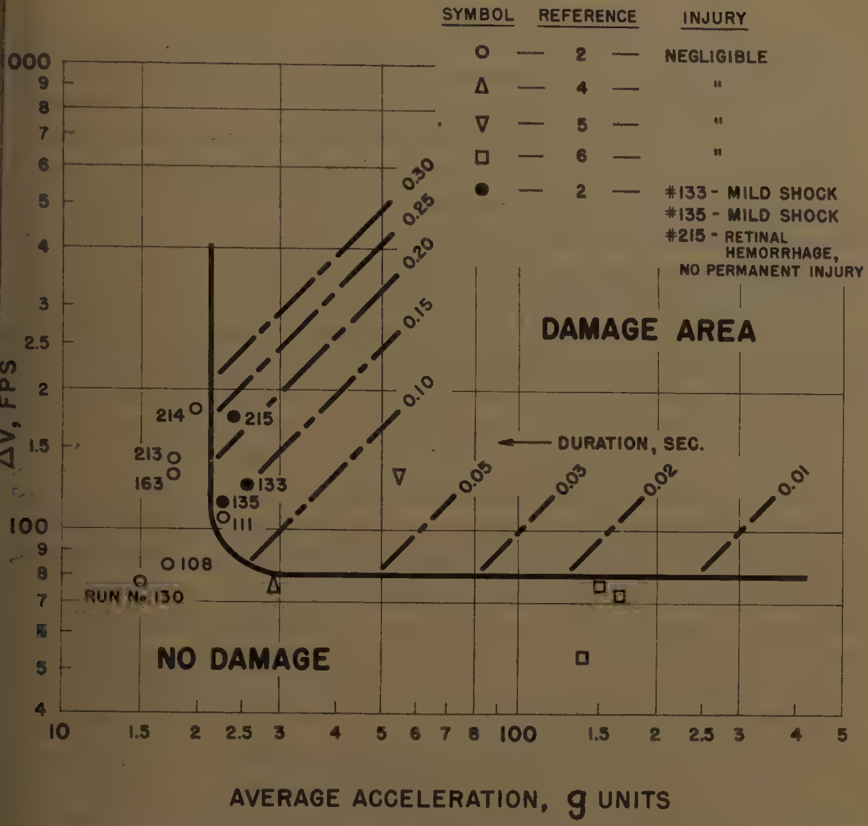


FIGURE 5. Impact sensitivity curve, after Kornhauser.[11] Average acceleraion (g) versus change in velocity (ft./sec.). Impact durations between 0.01 and .03 sec. given in dashed slanted lines. Asymptote values are approximately 20 g nd 80 ft./sec. No permanent damage observed below and to left of the curve.

he rate of onset of the acceleration or jolt is widely believed to play a ole in man's impact tolerance. Theoretically, it has been possible to how that jolt plays a role in determining the vertical asymptote value, ut apparently no role in determining the horizontal asymptote value.

Because the impact at landing may be severe, attention has been given o the use of impact bags and crush-up structure. Due to winds and surace waves, the attitude of the vehicle when it strikes the water is ssentially uncontrollable. The orientation of the man will be uncertain. or these reasons, where impact may come at a variety of angles, careful onsideration must be given to the coupling of the man in his space suit o his support system and to the coupling of this system to the vehicle. he space suit that the pilot will wear will require a specially designed nd integrated restraint system.

Weightlessness. The effects of weightlessness on man's physiological nctions and performance capabilities are the least known of all the acceleration effects encountered in space flight. Of the methods of producing or simulating weightlessness, the most useful currently is th parabolic flight in an aircraft. Short periods of zero g may be achieved fo times varying from 15 to 45 sec. The effects of prolonged weightlessness are not known and not likely to be known for some time. The first X-15 and the ballistic Project Mercury test flights will extend this time to 5 min. and subsequent orbital flights will extend the time to hours.

For the physiologist several interesting phenomena occur. Convection is absent, so that a candle will not burn under weightlessness. The expired breath will be reinspired in the absence of forced air circulation. The sudden occurrence of weightlessness in animal flights is reported to be associated with a sudden increase in pulse rate. This perhaps occurs because of the alteration in transmural pressure and thus in the caliber of some blood vessels whose walls contain nerve endings responsive to stretch. This alteration in pulse rate apparently adapts slowly over several hours. Although food can be swallowed readily by man if it is presented at the back of the throat, the valve between stomach and esophagus is incompetent and food regurgitates easily when the stomach pressure is elevated. A curious finding is the absence of the sensation of urgency when the bladder is full. This sensation also can be relieved in the laboratory by the simple expedient of standing on one's head. Apparently the nerve endings giving rise to this sensation lie at the base of the bladder, while the dome is free from such nerves.

There has been considerable speculation concerning the effects of prolonged weightlessness on the circulation and on the muscular system.[13] It is proposed that entering a high g field after prolonged weightlessness will be like jumping out of bed after a long illness. It is proposed also that muscles will tend to atrophy because of the absence of gravitation, which generally serves as stimulus to good muscle tone through the action of tendon and muscle-stretch receptors. Whether these effects will occur, most physiologists and physicians are concerned that man have adequate exercise while under zero g and that undue cramping does not occur.

A serious threat to the welfare of the astronaut would be the occurrence of motion sickness. While susceptible individuals can be screened by means of Keplerian flights, it is not known if such a screening will be adequate for prolonged weightlessness. In susceptible individuals nausea and vomiting may occur.[14] The latter would be a catastrophic event in a closed space suit unless a container was provided.

When space flight becomes a "shirt-sleeve" affair, many special provisions for operation in the weightless state will be required. It is important to recognize that all of man's daily functions and, indeed, the function of all the space vehicle's equipment must be examined with a view to the effects of weightlessness. The physiologist is likely to pass off facetiously some of these difficult human mechanical situations as engineering problems, because at present his only solutions are pilot selection and training and the use of drugs. The latter step, he is reluctant to consider at the present until the problems are defined more firmly.

Important studies of man in the weightless state are those related to man's capability to perform complex tasks. The present data, particularly those of Brown,[15] suggest that the restrained man can perform quite adequately during multiple exposures to short periods of weightlessness. What will his capabilities be during prolonged zero g? Upon the answer to this question may hinge the future role of man in space as pilot, as navigator, as explorer, or as scientist.

Noise and Vibration

During launch, powered flight, and re-entry the two principal sources of noise and vibration are the rocket motors and aerodynamic disturbances. These unwanted environmental effects may have an important bearing on man's efficiency in transmitting and receiving communications and in motor and visual performance, particularly when associated with the other environmental stresses of these phases. An estimate of the bioacoustic environment of the space vehicle and a prediction of the human response o this environment are required in order that protective measures may be undertaken if they appear necessary.

Noise. In estimating the bioacoustic environment, von Gierke[16] assumed a missile diameter of 7 to 15 feet and a length of 75 to 125 feet. The space cabin is assumed to be in the nose cone of the missile and hus is located optimally with respect to booster noise. For the missile on the ground, a typical blast deflector bucket, that deflects the jet by 90° is also assumed, so that sound-pressure levels during static firing are higher than those during flight. In order to calculate the sound-pressure levels incident on the ear canal, assumptions were made concerning transmission losses through the cabin wall (1-inch copper shell) and the absorption of the interior room (interior absorption coefficient of 0.66). In addition, the presence of a pressure suit and a pressure helmet with closed visor was assumed, which provides about 30 db attenuation in he 1200 to 2400 cps band and relatively little attenuation below 300 cps.

The resulting calculations are shown in FIGURE 6. The launched ocket noise shown is the maximum noise immediately after take-off. This oise level may be expected to decrease approximately with the second o the fourth power of vehicle velocity. The low-frequency components of he noise are close to pain threshold, but damage is not expected because f their short duration. If the conditions assumed prove correct, current earphones that provide signals up to 90 db or more should achieve a 10-db signal-to-noise ratio, even on the launch pad. Modification of the cabin wall in the interests of lighter weight, however, will increase these noise estimates that are based on the so-called mass law alone.

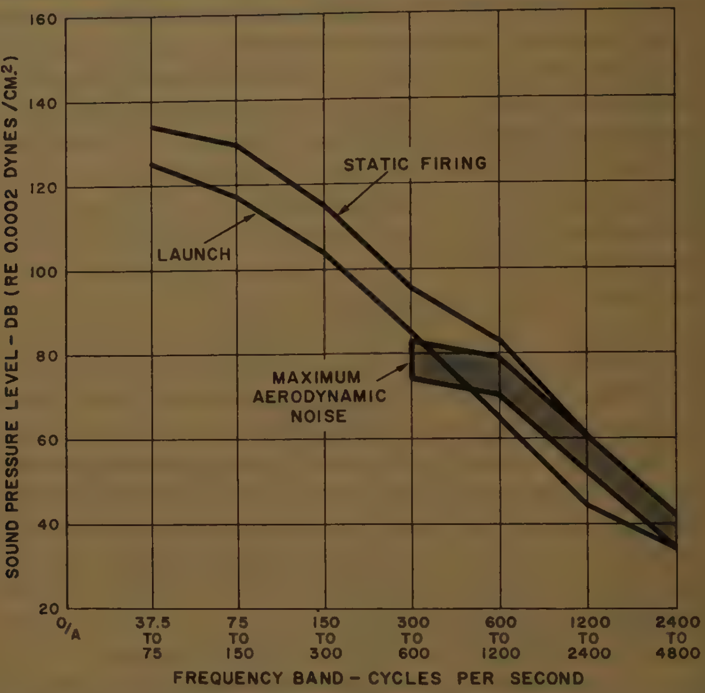


FIGURE 6. Bioacoustic environment. Sound pressure (db) versus frequency (cps) for missile static firing, launch, and vehicle re-entry noise (estimated), Reproduced by permission from *Noise Control.* [16]

If it is assumed that aerodynamic noise varies as the second to third power of the indicated air speed, depending on the frequency band, this component of the total noise will pass through a maximum during powered flight and then decrease as the vehicle leaves the atmosphere. Under the above assumptions, the maximum sound-pressure level at the ear canal due to boundary layer noise also has been calculated and is shown in FIGURE 6. These calculations have been confirmed by measurements during hypersonic flight. In contrast, the conditions for the production of aerodynamic noise during re-entry are quite different. Assuming particular re-entry profiles, Callaghan[17] has computed over-all re-entry sound-pressure levels outside the nose cone that are approximately the same as those occurring during the launch phase. Because the time of exposure is short, re-entry aerodynamic noise is unlikely to pose a major problem, but experimental data are needed to confirm these calculations. Data recorded from re-entering ballistic missile nose cones, which differ from a manned space vehicle in weight and geometry, indicate that the maximum sound energy is in the high-frequency range. No estimates of the frequency spectrum of re-entry noise are available.

Vibration. No general prediction scheme exists for the evaluation of structure-borne vibration because the frequency and levels depend markedly on the specific details of engine and missile structure and the aerodynamics and operation of the craft. It is known that man absorbs vibrational energy maximally in the frequency range from 0.5 to 20 cps and that several mechanical resonances in the body structure occur in this frequency range. Although over-all vibration spectra for particular missile systems may not be known for large vehicles, low-frequency resonances do occur (FIGURE 7). Although few data are available on launch and in-flight vibration levels that extend to such low frequencies, von Gierke[16] concludes that the vibrations from booster engines constitute no serious hazard to man, principally because of their short duration. Greatest severity is expected when the missile shudders on the pad at the moment of launch. The transverse low-frequency vibrations caused by corrections of the guidance system probably will generate only 1 g or less and will be amenable to engineering control.

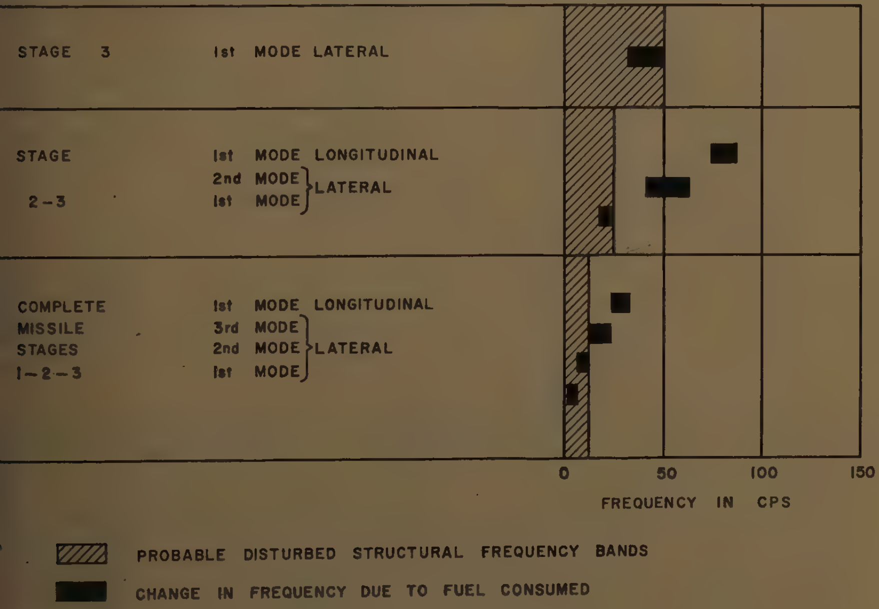


FIGURE 7. Missile vibration spectrum. Reproduced by permission from *Noise Control.*[16,18]

The resonances of importance in the body structure of man are in the thorax-abdomen system. For a constant acceleration input abdominal acceleration is plotted in FIGURE 8 for longitudinal vibration on a shake

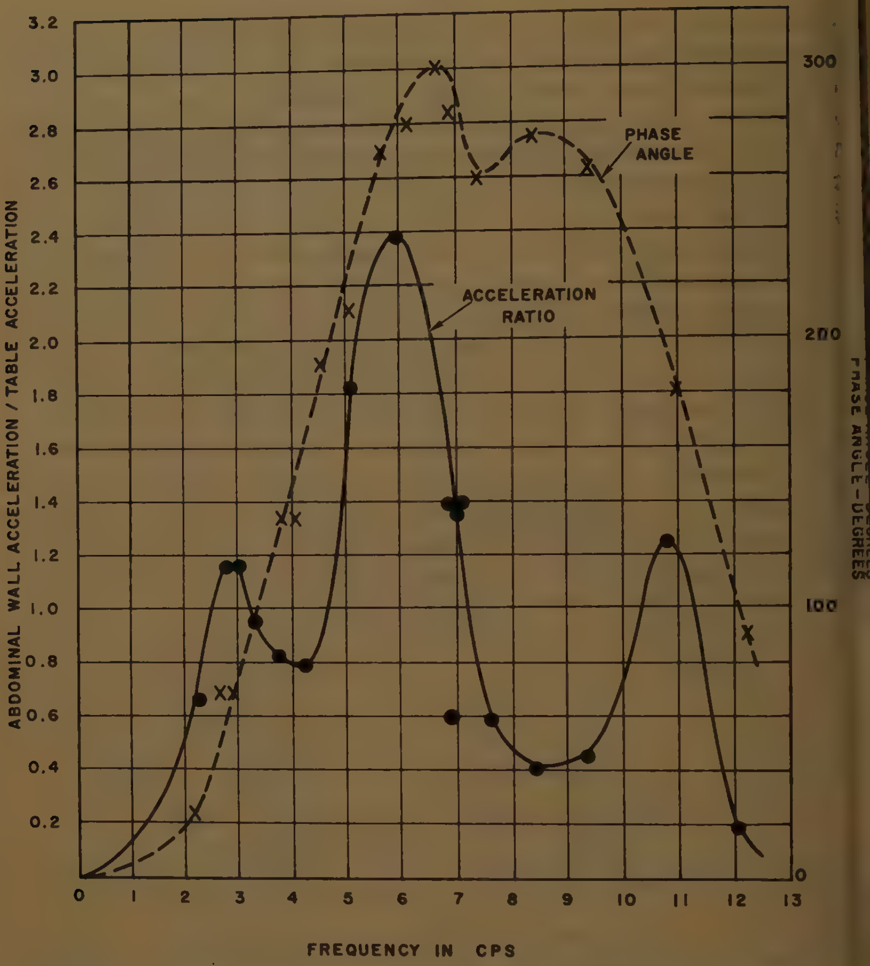


FIGURE 8. Abdominal wall resonances of supine human vibrated along long axis. Reproduced by permission from *Noise Control*.[16]

table. Peak resonance occurs at approximately 6 cps, although other resonances occur at 3 and 10 cps. Vibration tolerance depends strongly on the direction and the nature of the body support and restraint harness employed. Little or no data are available for complex vibrations in multiple axes. Goldman[19] has accumulated tolerance data for humans from the literature, as shown in FIGURE 9, for continuous sinusoidal vibration parallel to the long axis.

Because of the simultaneous occurrence of transverse g, vibration, noise, thermal stress, and the possibility of adverse interactions, an adverse effect on the ability of the pilot to perform in a launch emergency may occur. Thus, there is a real need for automatic emergency devices nd for intensive pilot training under simulated launch conditions, such s static rocket engine firings. Future single-chamber rocket engines vith thrusts in excess of one million pounds may produce such extremely igh-intensity low-frequency noise and vibration that extensive protection f the pilot may be required. The new vertical accelerator at the Biacous-ics Laboratory of the Wright Air Development Center, Wright Air Force ase, Ohio, which is especially designed to study high-amplitude (10 eet) low-frequency (0 to 10 cps) vibration effects on man should enlarge ur knowledge in this area greatly.

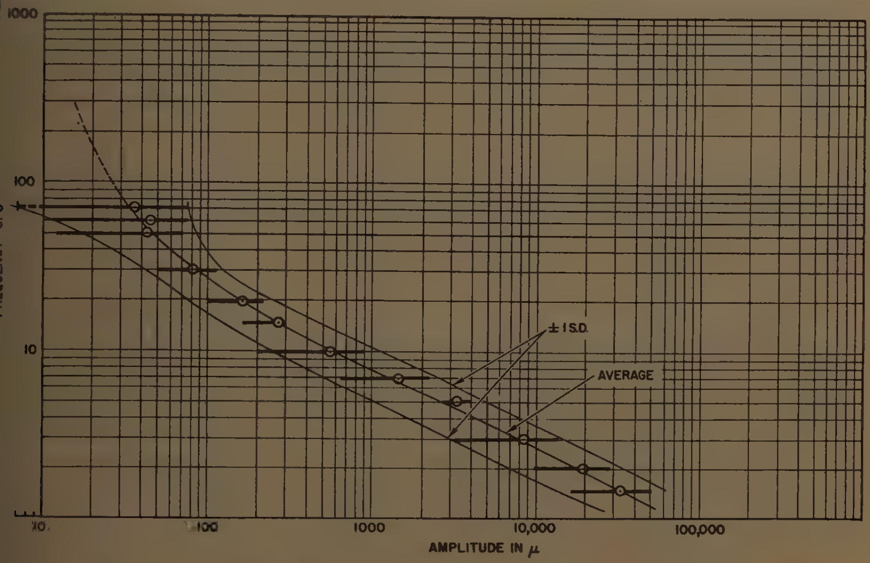


FIGURE 9. Human vibration tolerance (frequency versus amplitude) for eated man vibrated vertically. Average values and standard deviation for maxi-um tolerable levels are indicated. Reproduced by permission of McGraw-Hill ook Company, Inc.[19]

Control of the Gaseous Environment

The most important determinant of the design of a gaseous environ-ental control system for early space flight is the requirement for a space uit. While it is possible to look forward to an ultimate "shirt-sleeve" peration, for early missions the pilot will need a space suit to protect im against the thermal stresses of re-entry and the threat of cabin ecompression. While a space suit helps ensure the pilot's safety, penal-es of discomfort, lack of mobility, and problems of elimination are in-urred. The environmental control system must operate then, as (1) an tegral closed cycle with the space suit, (2) a closed-cycle system erving both pressure suit and cabin (suit visor open), or (3) an open-ycle system with the pressure suit in emergencies. In closed-cycle peration, oxygen is supplied by a pressure-demand system, and carbon dioxide and water vapor are absorbed. In open-cycle operation, oxygen is delivered at a rate sufficient to maintain the CO_2 concentration at acceptable levels, and the excess is vented to space. Integral with the system is a method of heating or cooling the air.

For design purposes, an oxygen partial pressure of at least 150 mm. Hg and a carbon dioxide partial pressure of less than 7 to 8 mm. Hg are desirable requirements. Because of the mode of ventilation of the space suit, an air temperature of 50° F. and a water vapor partial pressure of approximately 5 to 10 mm. Hg are required at the suit inlet in view of the predicted thermal loads. The ambient air in the space capsule and the pressure suit will consist, then, of a mixture including water vapor, which is ubiquitous and therefore always in ambient air; oxygen, which is essential; and amounts of carbon dioxide compatible with life. A fourth gas such as nitrogen also may be presented to dilute the oxygen. Thus the system may contain either three or four gases, and the total pressure may be maintained between one third and one atmosphere. Problems associated with establishing and maintaining either a three- or four-gas system will be discussed next.

Four-gas system (O_2, CO_2, H_2O, and N_2). In considering a four-gas system, the physiology student's familiar exercise of death in a closed space is informative. Suppose a closed four-gas system of normal atmospheric composition in which there has been a complete failure of the environmental control system. There is no ventilation, no CO_2 absorption, and no oxygen replacement. How long could a man live in this atmosphere? He uses up oxygen, giving off 0.8 as much CO_2, by volume, plus some water vapor from the lungs. When the partial pressure of O_2 falls to about 70 mm. Hg the man becomes hypoxic, then unconscious, and death ensues. In this closed space the CO_2 around the man increases. At a level of 50 to 60 mm. Hg partial pressure, the man is in severe trouble.

How long the man can live depends on the size of the chamber. From size of the chamber, the initial and the least tolerable oxygen partial pressures, the quantity of oxygen available to the man is calculated. This quantity, divided by the man's metabolic oxygen consumption rate per hour, is the number of hours available to the man. A corresponding calculation can be made for carbon dioxide; whichever period is shorter will be the survival time of the man.

For example, assume a metabolic O_2 consumption of 0.5 l./min. (twice basal metabolic rate), an initial O_2 partial pressure of 153 mm. Hg, a final O_2 partial pressure of 60 mm. Hg, and a chamber volume of 4000 l. For a 93-mm. Hg oxygen tension difference

$$(93/760 \times 4000) = 490 \text{ l. of } O_2 \text{ consumed}$$

and

$$490/0.5 = 980 \text{ min. or } 16 \text{ hours survival time}$$

For CO_2, an output of 0.4 l./min., an initial concentration of 0, a final concentration of 0.06, and the same chamber volume yields

$$\frac{0.06 \times 4000}{0.40} = 600 \text{ min. or 10 hours.}$$

In this case CO_2 determines the survival period.

A number of interesting problems are related to this closed-chamber problem. At what rate must the chamber be ventilated to maintain the CO_2 level at 1 per cent? The flow rate is given by the ratio of the CO_2 output per minute of the man divided by the desired CO_2 concentration in the chamber. For a CO_2 concentration of 1 per cent and a CO_2 metabolic output of 0.4 l./min., the flow rate is 0.4/0.01 or 40 l./min. (1.4 cfm). Notice that the ventilation rate is independent of the size of the chamber and that the equation applies equally well to a space as small as a space suit helmet or as large as a submarine. The ventilation rate is not at all critical. At one third of this flow rate the CO_2 level rises to 3 per cent, which is not dangerous for short periods. Such flow rates result in an extremely wasteful open-cycle system for a space vehicle.

A second problem consists of the effect of a chamber leak on the composition of the chamber gases. Probably all space cabins will leak or outgas to some degree, and the magnitude of the leak will have a bearing on the quantity of gases to be transported, as well as on the gas composition. For a four-gas system in space, a leak would result in a gradual loss of nitrogen, and in a requirement for storage of additional oxygen lost by leakage. If the space cabin volume is 4000 l., the nitrogen volume would be approximately 3160 l. at 15 psia. At a leak rate of 0.1 psi per hour, approximately 70 hours would be required before the oxygen concentration would reach 60 per cent. A leak rate of this value would be acceptable for the flight regime under consideration if it were certain that this leak rate would remain at this value following launch acceleration and vibration. For a leak rate of 1 psi per hour, only 7 hours would lapse before the O_2 concentration reached 60 per cent. For long flights it would be necessary to carry additional nitrogen, measure its concentration in the environment, and meter appropriate quantities into the environment.

Outgassing during prolonged residence in space will require study. It is possible that the permeability of the cabin walls in a nearly complete external vacuum will result in an alteration in the composition of the internal gaseous environment. Because certain metals and other materials are differentially permeable to various gases, it may be possible to bring about desired atmospheric alterations by appropriate selection of materials.

Three-gas system (O_2, CO_2, and H_2O). Suppose that the subject, who has been breathing room air, is switched suddenly to pure oxygen at the same pressure. His respiratory rate and depth hardly change; his metabolism remains the same. Nitrogen is washed out of his lungs in abou 3 min. and his remaining body tissues are denitrogenated in about 1 hour. If no CO_2 absorption is provided, the maintenance of the three-gas system requires that the chamber be ventilated continuously with pure oxygen at the same rate as in the previous calculation. If CO_2 is absorbed oxygen may be bled into the chamber by a demand system.

A review of the literature of oxygen toxicity by Mullinax an Beischer[20] indicates that, for operational purposes, residence in atmospheres of 100 per cent oxygen at normal atmospheric pressures is permissible for at least 12 hours. Although some controversy surrounds the tolerance of man to 100 per cent oxygen at sea level, the lower oxygen limit for man is more clearly established. An equivalent altitude o 40,000 feet (2.8 lb./sq. in.) on pure oxygen predisposes to nausea, vomiting, headache, and impaired mental response. Surges to lower values should not occur except in emergencies and then are tolerable for only about 30 sec. After 15 sec. of consciousness and an unconscious interval of 15 sec., death will occur if the pressure is not restored. Thus, a total pressure between one-third and one-half atmosphere absolute has been selected as an appropriate value for the three-gas system.

If the space cabin were filled with oxygen at one-third atmosphere, if no CO_2 were present, and if there were no leaks, a failure of the environmental control system could be assessed using the calculations given above. In a cabin volume of 4000 l., about 760 l. of oxygen would be available, sufficient for about 25 hours. Carbon dioxide levels of 6 per cent would be reached in 10 hours. If there were an appreciable leak rate, CO_2 survival time would be lengthened, but O_2 survival time shortened.

Operationally, the establishment of a 100 per cent oxygen atmosphere presents problems due to fire hazard. If the space cabin is purged with oxygen prior to launch, a period of time will elapse during which the cabin environment consists of 100 per cent oxygen at atmospheric pressure. If purging takes place at the moment of launch or during launch, provision for prior denitrogenation of pilot must be made. In the latter case the purge gas must be carried along, thus incurring a weight penalty. Purging during the short launch period probably would leave residual nitrogen in the cabin.

The total pressure in the system may be established by opening the cabin to the outside during the launch period and sealing the cabin again at the appropriate altitude. During re-entry, the process is reversed. It is possible, however, if the cabin structure permits, to allow the pilot to "breathe-down" the pressure in his capsule to the value at which the pressure-demand system commences operation.

The fire hazard, however, is real. Simons and Archibald[21] have demonstrated that the combustion time of cotton twill varies directly with the oxygen partial pressure and inversely with the nitrogen partial pressure or that of other diluent gases. However, it is difficult to demonstrate arcing or oxidation in mechanico-electrical systems such as microswitches and potentiometers operated for extended periods in 100 per cent oxygen atmospheres. Strict attention must be paid to maintaining the cabin free of static electricity, open electric connections, grease, and oils. Extensive cleaning of the cabin will be required prior to launch to rid the cabin of free objects, dirt, and dust which would contaminate the atmosphere under weightlessness. If cleaning solvents are used, they must be chosen for low combustability and for the absence of toxic effects if residual quantities are retained in the closed environmental system. Similarly, attention must be paid to the cleanliness of purge lines so that contaminants are not introduced into the environment at the last moment.

Gas expansions. Decompression of the space cabin could occur from at least two causes: (1) structural failure, and (2) meteorite puncture. Decompression is usually characterized as *explosive* if the event lasts 1 sec. or less, or *rapid*, if the decompression time lasts more than 1 sec. In explosive decompression, rapid expansion of internal gases in the pilot may produce damage; whereas in rapid decompression, lasting over many seconds, anoxia or aeroembolism may be the cause of death.

Explosive decompression. When the cork is pulled from a champagne bottle, the "pop" is due to the immediate mechanical expansion of the gas between the cork and the liquid surface. This is then followed by evolution of carbon dioxide gas, previously in solution under pressure in the liquid phase. Much the same thing happens in man when he is transported from one atmosphere to a fraction of an atmosphere ambient pressure. Air rushes out of his lungs. If the subject holds his breath and prevents outflow of gas, the chest expands, the lung tissues may overdistend, and the lungs may even rupture.

Gas in the stomach and intestines expands in volume. The stomach or the colon can accommodate a volume of about 1½ l. before cramping pains become unpleasant or the transmural pressure high. Most subjects who have not eaten recently and who are ambulatory contract the abdomen automatically to maintain almost no gas in the intestines.

If the mask of the space suit helmet were open, and the capsule containing the man in his suit suddenly lost pressure, air would expand in the lungs and rush out through the tracheal resistance, which is about 1 cm. H_2O/l./sec. If air also expands in the space suit and rushes out through the neck or face seal resistance, there may be a balance of forces such as to prevent overdistension of the chest, provided that the time constant (RC) for the compressibility of gas in the lungs and airway resistance is about the same respectively, as for the gas in the suit and the neck outflow resistance. If the gas in the lungs is 3.5 l. at one-third atmosphere, it would have a compressibility of 0.0012 l./cm. H_2O against a resistance to outflow of 1 cm. H_2O/l./sec., giving a time constant of 0.0012 sec.

Rapid decompression. In explosive decompression, the area of the orifice is large with respect to the total volume of the cabin, and the decompression time is less than 1 sec. The time of decompression to a vacuum, t, is given by Konecci[22] as

$$t = \frac{144V}{AC} \ln \frac{P_0}{P}$$

where V = volume of the cabin in cu. ft.; P_0 = initial cabin pressure, psi; A = orifice size in sq. in.; P = instantaneous cabin pressure, psi; and C = sonic velocity of air flow (1130 ft./sec. at 68° F.).

Suppose that a space cabin volume of 120 cu. ft. is punctured by a meteorite. The area of the orifice produced is 1 sq. in. In case I, the cabin atmosphere is composed of 20 per cent oxygen with a total pressure of 15 psia. In case II, the cabin atmosphere is composed of 100 per cent oxygen at 5 psia. How long does it take for the partial pressure of oxygen to fall to anoxic levels? In case I, decompression may proceed to 10.1 psia (10,000 ft.) before anoxia occurs. In case II, decompression may proceed to 2.8 psia before anoxia. With the above equation, the following results are obtained:

	P_0 (psi)	P (psi)	t sec. (1 sq. in.)	t sec. (1 sq. cm.)
Case I	15	10.1	6	35
Case II	5	2.85	9	54

For small holes, an absolute pressure of 5 psi appears to provide a somewhat longer decompression time. In the above, the oxygen added by the demand system is neglected. The bleed-in of additional oxygen would prolong the decompression time in both cases.

Summary: Three- Versus Four-Gas System

Each of the two systems discussed above presents advantages and disadvantages. The problems of the three-gas 5-psi environment involve the possibilities of:

(1) Oxygen toxicity, because of the requirement of breathing 100 per cent oxygen at atmospheric pressure for a number of hours during the count-down procedure.

(2) Atelectasis, thought to be due to a gaseous environment containing no inert gas. Probably the production of atelectasis requires a longer time

and perhaps O_2 at pressures greater than will be associated with the present mission.

(3) Denitrogenation, a requirement due to the rapid decrease in cabin pressure during exit. This is presumably not a problem because of prior denitrogenation or the 100 per cent oxygen breathed during count down.

(4) The fire hazard, associated with 100 per cent oxygen at atmospheric pressure in the cabin before and during launch.

The problems of the four-gas 15-psia environment are:

(1) A low leak rate, so that the oxygen, replaced on demand, will not reach toxic levels during the mission. The expected leak rate is such as to allow the present mission if launching stress does not increase the leak rate.

(2) The requirement for additional cabin wall strength to support a larger pressure differential. This appears to be feasible without a significant weight increase.

(3) The lack of an adequate on-the-shelf monitoring and metering method for nitrogen adaptable to space cabin use.

(4) A shorter time to anoxia in the event of decompression.

(5) The necessity of carrying the required weight of nitrogen, which serves no useful metabolic purpose.

The requirement for a pressure suit plays an important and probably deciding role in the selection of the gaseous environment. Current pressure suits support a pressure differential of only 5 psia. If decompression were to occur from a 15-psia 4-gas atmosphere, a shift to an atmosphere of 100 per cent oxygen would be required to support the man. Such a shift would require purging of the suit with oxygen. In essence, a second atmospheric control system would be required for this emergency. Alternately, a 15-psia differential suit must be developed.

From the foregoing considerations, the presently more acceptable solution is that of the three-gas system. If slightly greater total pressures can be used (for example, 7 psia), 1 to 2 psia of nitrogen might be included. Fire hazard must be brought to acceptable levels by good engineering practice and further consideration given to the launch procedures. For future consideration the four-gas system appears to have significant advantages.

In FIGURE 10 is shown a schematic diagram of a three-gas 5-psia system. The system is characterized by a double oxygen supply, redundant valving, and multiple modes of operation that will impart the necessary reliability to this critical system.

Temperature Control, Metabolism, and Nutrition

In orbit the thermal energy generated by the pilot and his equipment, either incident on the vehicle or dissipated into space, must be balanced

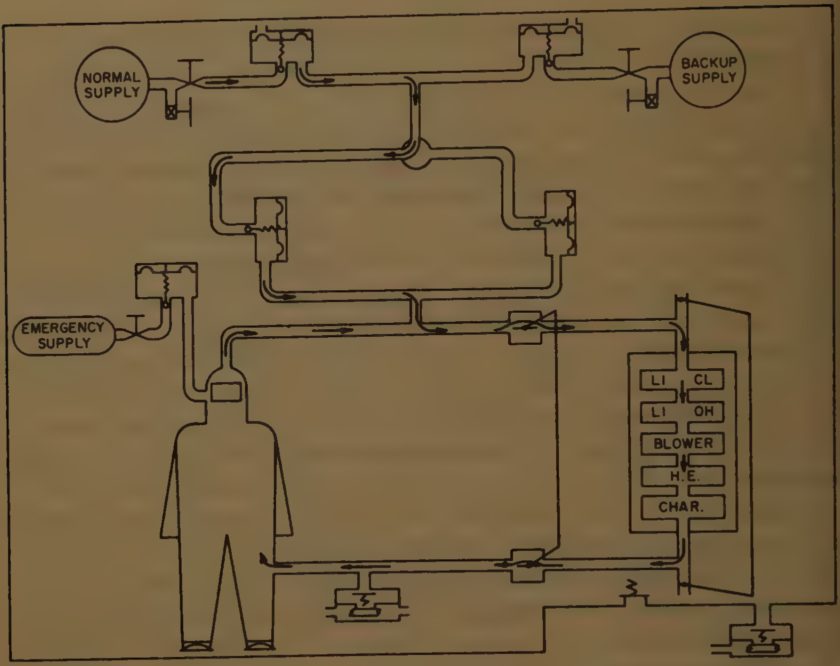


FIGURE 10. Environmental control system. Oxygen from high-pressure source is supplied by reducing value, manifold, and demand regulator. Closed suit circulation is shown. Conditioner contains LiOH, LiCl, blower, heat exchanger, and activated charcoal.[1]

at temperature levels appropriate not only to survival but to the operating efficiency of the man in his space suit. For disposing of thermal energy generated within the vehicle, the cooling system that is conceptually the most efficient for long-term use is radiation of energy into space. This entails no mass transfer within or from the vehicle. By varying the absorbtivity-emissivity ratio of the outer surface of the vehicle, a heat balance can be achieved for net outward heat fluxes of 0 to 90 B.T.U./hour/sq. ft. within the temperature range of from –80° to +100° F.

A fundamental difficulty is the transfer of heat from its source of generation to the radiating surface. In the range of internal temperatures desired, the net radiant heat transfer between internal structures and walls is small. Natural convection is absent in the weightless state; therefore, most of the heat must be transferred by conduction or forced convection. Providing for these modes of internal heat transfer is a chief source of system weight. Mission duration is also a decisive factor in the choice of a cooling system. For example, for very short periods of time, such as launch and re-entry heating, heat sinks are often the lightest and most efficient. For somewhat longer periods (hours), open-cycle mass-rejecting evaporative systems become attractive. In the case of flights of long duration (days, weeks, or longer), the greater fixed weight of conduction paths or closed-cycle circulating systems becomes more efficient and lighter over-all.

For example, the average power dissipation by the electronic components may be taken as 100 w, the batteries 50 w, the man 147 w, the environmental control system 100 w, and the chemical adsorbant reaction (CO_2 and H_2O) 30 w. The total energy involved in a 48-hour mission is thus approximately 20,500 wh. at a 427-w average rate, of which 7200 wh. is from components and power supplies.

A study of the orbital heat balance, including variations in geometry, thickness of insulation, external surface radiation characteristics of the vehicle, and the requirement for a pressure suit, indicates a requirement for a cooling system of the evaporative type for early space flights. Air from the evaporative cooler is ducted directly to the ventilation garment beneath the pressure suit, where it is distributed over the body.

It is anticipated that, with proper design, the inner wall temperature of the space vehicle, during re-entry, will rise in a linear fashion, reaching a peak of 165° F. at the time of water impact. Cooling to the prevailing water temperature will then occur, the entire heating and cooling cycle taking about 1 hour. This thermal stress is entirely within man's tolerance when protected by appropriate clothing incorporating a ventilating system and an evaporative cooler supplying air to the suit at approximately 10 cfm, 5 to 10 mm. Hg partial pressure H_2O, and 50° F.

Webb[23] has shown that total weight loss due to sweating, the water retained in the clothing, and changes in pulse rate and body temperature are reduced markedly by ventilating the pressure suit with low-temperature (45° F.), low-humidity air at about 10 cfm if the air/wall temperature is of the order of 160° F. (FIGURE 11). At reduced rates of air flow, tolerance is reduced, particularly at higher ventilating air temperatures. For example, at 6 cfm and an air/wall temperature of 160° F. performance is impaired after 2 hours if the ventilating air is 60° F. and 5 per cent relative humidity. At 3 cfm performance is impaired after little more than 1 hour, and the human tolerance limit is reached just before 2 hours. In more recent experiments, Webb (personal communication) demonstrated that men in ventilated heavy impermeable clothing can withstand a ramp thermal transient that increases at the rate of 100° F./min., peaking at over 500° F.

For the 2-day encapsulation the metabolic requirement of the pilot will approximate 1 MET or 50 kcal./sq. m./hour (FIGURE 12). If we overdesign to the extent of a ninety-fifth percentile man (2.08 sq. m.), the hourly metabolic rate is then 104 kcal. If this is doubled as a safety factor (2 MET), the design level becomes 208 kcal./hour or, for a 48-hour encapsulation, a total of 10,000 kcal.

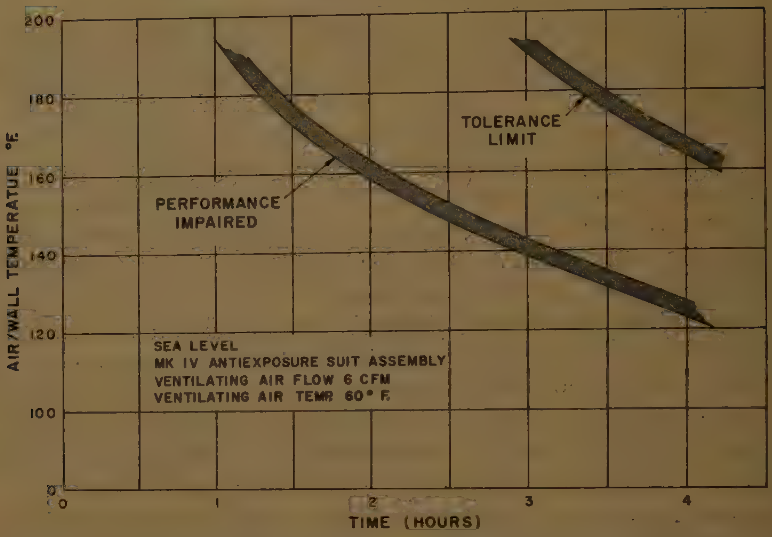


FIGURE 11. Human temperature tolerance with anti-exposure suit and ventilation garment. Reproduced by permission of General Electric Company.[23]

For a respiratory quotient (R.Q.) of 0.85 and an oxygen caloric equivalent of 4.8, the oxygen requirement is 2080 l./man/48 hours. The CO_2 absorber capacity should be 1770 l./man/48 hours.

The insulating capacity of the pressure suit is approximately 2 CLO. Standard calculations[24] indicate that an environmental temperature of 65° F. should be comfortable at approximately 1 MET. For 2 MET a cabin air/wall temperature of 50° F. is required. Radiant transfer at 2 CLO may be as little as 20 per cent of the total heat loss. Generally, because of inactivity, a metabolism of 1 MET has been observed in pressure suit experiments. Because of the complex construction of the suit (ventilation garment, aluminized outer surface), heat loss is largely by convective and evaporative routes. In particular, it should be noted that the use of convection and body water evaporation as modes of heat loss requires attention to the water balance of the pilot.

The food requirement in orbit is met with low-residue foods. Certainly no more than 2500 kcal. per day will be required, and this can be reduced substantially without ill effects for this short period. Vitamin and mineral supplements can be neglected.

Because of the short duration of the trip and the presence of the pressure suit, the problem of waste elimination must be met by feeding a low-residue diet for several days preceding the trip. Urinary elimination will require a modification of the pressure suit if samples are to be collected externally. Although such heavy complex clothing imparts protection against elevated temperatures and explosive decompression, it may represent a liability in the thermal comfort zone, limiting the mobility and performance of tasks by the occupant.

Metabolism

(95th percentile: 200.8 lb., 73.1 in., 2.08 sq. m.)

Metabolic rate	100 kcal./sq. m./hr. (2 met)
	208 kcal./man/hr.
	10,000 kcal./man/48 hr.
RQ = 0.85	2080 l. O_2/man/48 hr.
	1770 l. CO_2/man/48 hr.
RQ = 0.70	1456 l. CO_2/man/48 hr.
RQ = 1.0	2080 l. CO_2/man/48 hr.

Water Balance

Intake	Water	2000 ml./day
	Food	500 ml./day
		2500 ml./day
Output	Insens. loss	1000 ml./day
	Urine	1500 ml./day
	Stool	——
		2500 ml./day

FIGURE 12. Metabolic requirements for ninety-fifth percentile man.

Biomedical Monitoring

The primary scientific purpose of a manned space flight is the acquisition of fundamental data on the physiological changes and the performance capabilities of man in the weightless state. Such scientific data are normally amenable to lengthy postflight reduction and analysis. A number of the environmental and physiological measurements, however, relate directly to the safety and well-being of the occupant, and it seems desirable that at least some of these be ascertained on earth in real time and appropriately processed for immediate decision and action. The stringent space, weight, and power allowances for transducers and telemetry posed by early space flight attempts place serious limitations upon the permissible number and variety of measurements. It is therefore important that the scientific and safety measurements be selected judiciously to yield the maximum significant information for the least practicable space, weight, and power penalty.

It is thus pertinent to describe the considerations and criteria entering into the choice of biomedical measurements for space flight and to discuss the techniques available and the problems associated with biomedical data transmission, reduction, and analysis. There are many unresolved problem areas. Indeed, biologists have only recently begun to think in general terms about handling biological data. The emphasis here will be upon the delineation of some of these problem areas for purposes of discussion and study. In general, the types of measurements to be made will vary with the duration of the mission. In TABLE 2 are listed some different kinds of space flights contrasted according to length of the mission, the appropriate passenger (animal or man), the data-handling technique (transmission, TR, or onboard recording, RE) and the type of data desired (engineering, physiological, performance, or monitoring data).

Short ballistic flights lasting 5 to 30 min. have as their primary purpose the engineering test of the space vehicle prior to orbital flight. Both animals and man would be suitable subjects. In these flights telemetry and onboard recording of engineering and physiological data are required. For flights consisting of single or multiple orbits, the measurements of primary experimental interest are those relating to the performance capabilities of the man or animal.

For ballistic and single orbit flight, it will not be possible to take significant corrective action from the ground in the event of a malfunction in the vehicle. Such missions will be under automatic control. In the case

TABLE 2

CLASSIFICATION OF SPACE FLIGHTS

Type of flight	*Duration*	*Subject*		*Data handling*		*Eng.*	*Data type*		
		Animal	*Man*	*TR.*	*RE.*		*Phy.*	*Perf.*	*Mo.*
Ballistic	5 to 30 min.	x	x	x	x	x	x		
One orbit	90 min.	x	x	x	x	x	x	x	
Multiple orbit	24 hr.	x	x	x	x	x	x	x	x
Lunar	2 weeks	x	x	x				x	x
Space station	months		x	x					x

f a flight consisting of one orbit, immediate re-entry is perhaps the only nergency action that can be taken. However, re-entry at other than the esignated landing site perhaps would be more hazardous than the com-letion of the prescribed mission because of the absence of adequate earch and recovery facilities.

When multiple orbit flights become possible and the engineering design roved, some physiological measurements will continue to be desirable, ut detailed engineering data no longer should be necessary. Rather, rovision must be made for simple monitoring of the vehicle and its assenger from the ground in such a way that rapid and effective action an be taken in the event of malfunction and incapacitation of the pilot. 'or lunar flights, lasting approximately 2 weeks, it is no longer possible o take effective emergency action from the ground. Monitoring information vill be required instead by the passenger on board. In space stations, nboard monitoring by the crew also would be required. In the event of ne malfunction of a multicrew space station, escape mechanisms or 'lifeboats'' should be available for re-entry.

In general, then, the types of measurements will depend upon the xperimental data requirement (the mission plan) and upon safety onsiderations.

Manned flight instrumentation. In TABLE 3 is shown a list of sensors nat might be used in an early manned space flight. These are arranged ccording to whether the measurements are made on the man himself, his hemical or physical environment, or his performance output. A number of varning signals displayed to the pilot also are included. For each sensor he presentation that is most applicable, either analogue (A) or digital D), the appropriate range, accuracy and, last, the requirement for onboard onitoring are shown. It is seen that a wide variety of phenomena must e instrumented, varying in accuracy requirements from precise to rela-vely inaccurate, in preferred presentation, and in range. The electro-ardiogram (EKG) and the respiratory depth measurement are not compat-ble with airborne sampling techniques, and each requires a continuous hannel.

The possibility of using sensors on the man himself has attracted con-iderable attention. The selection of these sensors depends upon the xperiment to be performed and the safety aspects. The considerable de-ate among biologists as to what sensors should be used arises because f varying experimental requirements. Multilead electrocardiography, lectroencephalography, skin resistance, and other measurements have een proposed. There seems to be general agreement, however, that the eart rate, the respiratory rate, and the body temperature must be meas-red for safety reasons. Respiratory depth would be desirable, but diffi-ult to achieve quantitatively. These measurements establish viability

TABLE 3

MANNED SPACE FLIGHT INSTRUMENTATION

Man	*Presentation*	*Range*	*Accuracy*	*Onboard monitor*
EKG (2)	A	0-2.5 mv	5%	
Respiratory rate	D	0-60 cpm	5%	
Respiratory depth	A	0-50 cps	5%	
Heart rate	D	0-300 cpm	5%	
Body temperature	D	80-115° F	1/2° F.	
Voice (send and receive)	A	300-2000 cps	5%	
Chemical Environment				
Humidity	D	0-90%	5%	
O_2 Reserve	D	0-3000 psia	1%	M
O_2 Flow rate	D	2-12 cfm	5%	
CO_2 Partial pressure	D	0-20 mm. Hg	5%	M
CO_2 Filter status	D	0-100%	10%	M
Cabin pressure	D	0-15 psia	1%	M
Suit pressure	D	0-15 psia	1%	M
Physical Environment				
Three-axes acceleration	D	Various		M
Vibration	D	0-5 g	5%	
Noise	D	140 db	5%	
Radiation rate	D	0-12 rem	5%	M
Air temperature	D	0-250° F.	3° F.	M
Wall temperature	D	700° F.	5%	
Meteorite impact	D			
Performance				
Roll position	D	±90°	± 1/2%	M
Pitch position	D	±90°	± 1/2%	M
Yaw position	D	± 180°	± 1/2%	M
Roll control	D	on-off		
Pitch control	D	on-off		
Yaw control	D	on-off		
Reaction fuel	D	0-3500 psia		M
Warnings				
CO_2-level warning		on-off		M
Cabin decompression		on-off		M
Attitude control system failure		on-off		M
Environment control system failure		on-off		M
Electric system failure		on-off		M
Radiation warning		on-off		M
May day		on-off		M

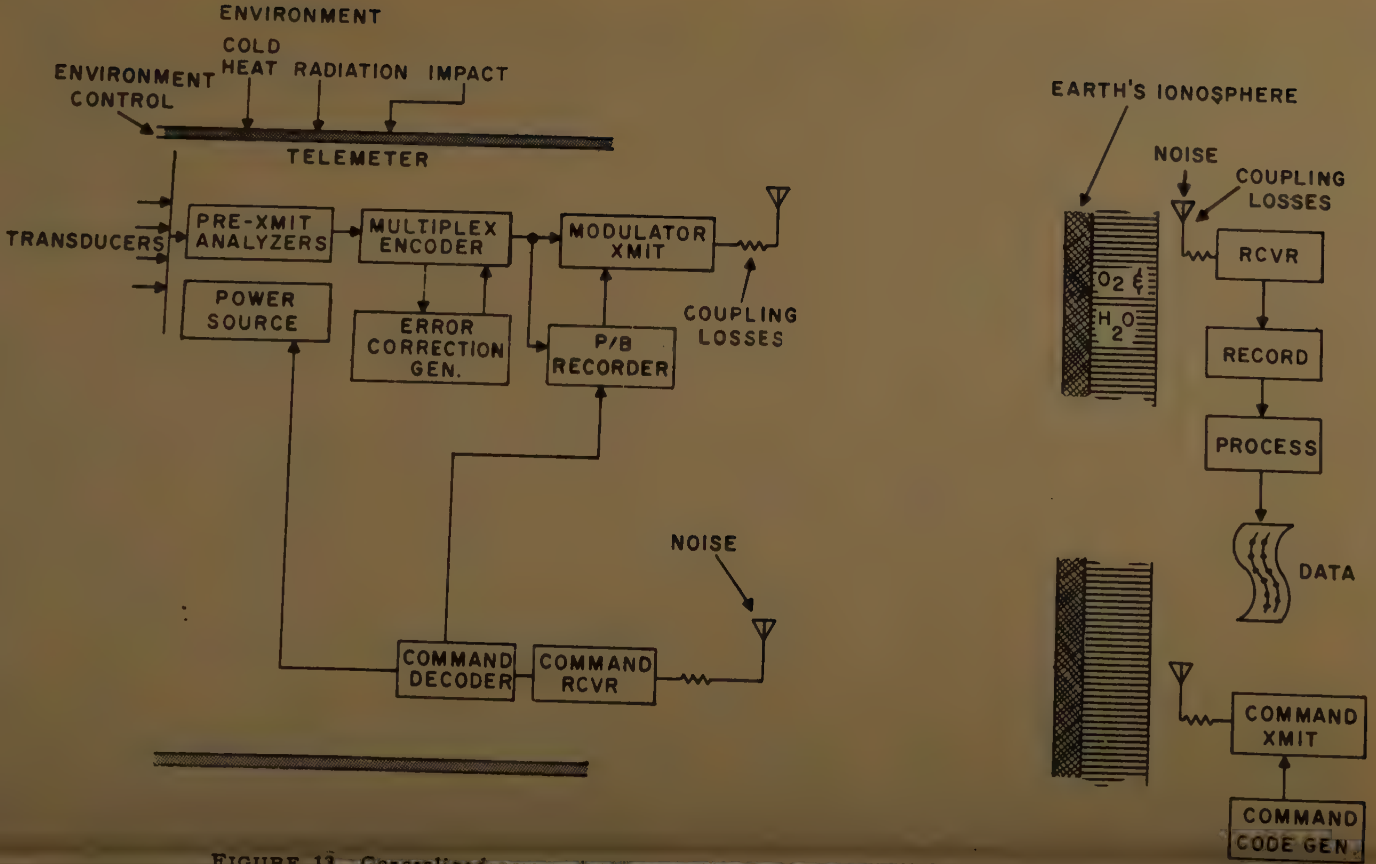
nd, taken together, are the most easily transduced measures of the over-ll physiological status of the individual.

All biological sensors must meet three criteria. First, ideally, the ensors should be stable and drift-free. A difficult problem arises if the nstruments must be calibrated frequently in orbit. Secondly, the instruentation on the man must mate satisfactorily with the space suit. The resence of the space suit presents considerable problems in the case of ome sensors. For example, considerable effort has been expended on the evelopment of a blood pressure sensor that can be used satisfactorily nder the space suit. Some study also has been devoted to the developent of satisfactory electrodes that maintain good electric contact with he skin of the man over a prolonged period. Finally, all sensors must ass a rigorous qualification testing program including such factors as cceleration, vibration, heat, and humidity. Whenever low-level signal utputs are produced by the transducer, stable amplification must be rovided.

The selection of sensors for the chemical or gaseous environment will epend upon the number and types of gases present. If, for early space lights, the space capsule atmosphere is composed of nearly 100 per cent xygen, no measurement of the partial pressure of oxygen would be reuired. This is because, in this environment, a measurement of the partial ressure of carbon dioxide and of water vapor and the total pressure would haracterize the environment satisfactorily. If an inert gas such as nitroen were present, a measurement of the partial pressure of oxygen or itrogen would be required. Because of the requirements of light weight, tability, and resistance to environmental stress, thermal conductivity ethods seem most appropriate for the measurement of gas concentrations.

An important part of early manned space flights is the study of man's erformance capabilities in orbit, particularly his ability to control his ehicle. For example, the establishment of the vehicle's position in pace can be accomplished by means of infrared horizon sensors and yros. The problem of how this information shall be displayed to the pilot ith sufficient precision, and what control aids will be required by the ilot is an open question. A number of devices are under development for is purpose. The man's output in terms of control motions can be transuced simply by means of switches and potentiometers.

Communication system. In FIGURE 13 is shown a generalized commuication system for an orbiting space vehicle. In the design of biological r psychological experiments in orbit, the biologist or psychologist needs general over-all knowledge of the capabilities and the restrictions of uch systems. Of particular interest are the possibilities for on-board nalysis of data. The use of such devices reduces the transmission band idth required by extracting only the salient features of the data and


ENVIRONMENT
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POWER SOURCE
ERROR CORRECTION GEN.
P/B RECORDER
COUPLING LOSSES
NOISE
COMMAND DECODER
COMMAND RCVR
EARTH'S IONOSPHERE
NOISE
COUPLING LOSSES
O_2 ₵
H_2O
RCVR
RECORD
PROCESS
DATA
COMMAND XMIT
COMMAND CODE GEN

FIGURE 13

iminating redundancy. Reduction in band width enhances the capacity the data link for a given transmitter power, or conversely, the reduced ınd width reduces the power required to relay the data. Transmission stortions must be recognized, since they deteriorate the signal-to-oise ratio (that is, accuracy) of the data at the output of the ground ceiver.

Of particular importance to the over-all communication system is the ne of contact with the space vehicle. For orbits at 150-mile altitude, ntacts of 8 to 10 min. occur when the pass is at the zenith. This is a ther short time for evaluating the over-all status of the vehicle and the an, for decision-making, and for taking action. Careful attention, there-re, must be paid to data reduction and display for monitoring purposes. ata obtained during passes near the horizon are likely to be distorted ıd subject to misinterpretation.

Monitoring. As indicated above, in initial flights the instrumentation ust be designed to provide useful detailed knowledge of the mechanical tegrity of the vehicle and the psychological and physiological functions the pilot. As greater and greater numbers of orbits are attempted and ore and more experience is acquired, the function of the instrumentation the capsule will change from that of accumulating physiological, sychological, and engineering data to that of monitoring the integrity of e capsule and the well-being of the man.

Monitoring, in general, is a function different from the accumulation of perimental data. Monitoring has a "yes or no" aspect such as "all is ell" or "all is not well." If everything is going well in the space hicle and all variables are within their normal ranges, the "all is well" gnal may be the only information transferred. Reduction of data in this ay would conserve power markedly. However, in the event of a malfunc-on, as much data as possible would be required so that sufficient band idth must always be available for this purpose.

If "all is not well," what sort of information does the monitor of a ace vehicle require? Among the most pertinent reports are: (1) What ıriable is changing? (2) In what direction is it changing? and (3) How st is it changing? Data displayed in this way might lead to better pre-ctions of the nature of the malfunction during the short contact time.

If more than one variable is changing, a correlation between appropriate ıriables may lead to additional information. Relatively small, light-eight, airborne cross correlators soon will be available commercially, t the uses to which they might be put in the biological realm remain to examined.

There are philosophical implications in the problem of monitoring for ologists generally. What is the information content of a long "normal" cord of a number of unchanging biological variables? The justification for such a record is that it can be re-examined at a later date in the lig of some new discovery. Whether we can afford this luxury in space flight questionable. Usually, additional new unmeasured variables are require

The problem of who shall monitor and where monitoring should occur i also unresolved. In view of the manner in which the orbit precesses, a undetermined number of ground observers in the field would be required t monitor a manned space vehicle effectively. Should these individuals b given the responsibility and the ability to abort the mission by initiatin re-entry? Alternately, monitoring could be carried out at a central locatio A large world-wide communication network would be required for thi purpose.

Study of Human Performance under Weightlessness

What will be the purpose of the first attempts to put man in space? Wha is the experiment, the mission? Given the demonstration of feasibili and safety, the most overriding question is what can man do, what are hi performance capabilities under weightlessness? It is generally believe that the engineering state of the art permits the attempt to put man i space. Physiologists generally agree that 24 hours in orbit poses n insurmountable threat to man. Rocket studies in this country and in th Union of Soviet Socialist Republics and what we know of the Soviet Laik experiment suggest no mysterious untoward physiological occurrence Animal experiments, which undoubtedly will precede the man in spac attempts, will explore these physiological problems further.

The performance capabilities of man in space must be studied if we ar to learn how to optimize his relation to his equipment in the spac environment. Optimization can occur only when man's role in the syste is understood by the equipment designer. Generally, this role is relativel specific in relation to any particular piece of equipment. Man has, however, a number of attributes that may contribute to any system. Huma sensory capacities may surpass those of instruments, particularly wher minimum absolute energies for sensory detection are concerned. Man i good at sizing up complex situations quickly, he is alert for impendin changes, and his flexibility provides insurance in emergencies. By mean of long-term memory and reasoning, man can make judgments where it i impossible to reduce all operations to logical preset procedures. On th other hand, machines excel man where speed and power are required, i routine matters, and in computations. A complex machine is capable o carrying on more different activities simultaneously than man. Man penalizes the vehicle because of the space, weight, and power required t support him. The mission plan is made complex by the pilot selection an training procedures required. Thus, it is only through careful study an understanding that the proper role of man in a man-machine system can b evaluated.

The experimental program for a manned space flight should consist of task regime to test the appropriate abilities of man in the weightless tate. These tasks, if they are to be effective measures of man's performnce, must be nondeceptive and realistic. They must have a plausible elation to man's actual role in a space ship, such as the actual control f the vehicle by the pilot. An important criterion in the design of these asks is that they should strive for maximum generalizability to other asks and other men. The results of a poorly designed task regime may be imited to particular instruments used in particular ways. Appropriate xperimental design is thus mandatory if data obtained in orbit are to be ubsequently applicable to other space vehicles. The success of the xperiment may very well depend upon this and on the establishment of ppropriate performance of base lines by extensive controlled ground aining.

Factor analysis. The problem of generalizability of psychological data s a familiar cross that every experimental psychologist bears. For examle, the findings from most motor skill studies are limited severely to the articular instruments used in particular studies. The same limitation ppears when an attempt is made to generalize from perceptual data, as istinguished from the more generalizable but less critical threshold data.

Some success in getting at the generalizable elements of behavior has een achieved through the techniques of factor analysis. In this techique, many discrete bits of physical and verbal behavior are tested for eir correlations. Usually, many hundreds of these separate bits will nd to cluster into a dozen or less groups called factors. For example, e Minnesota Multiphasic Personality Inventory consists of a handful of cales arrived at in this way, and the United States Employment Service, ashington, D.C., concerned less with personality than with job aptitudes, as identified nine or ten useful factors.

By an emphasis on primary abilities (factors) in an experimental design, e trap of accumulating data whose utility would be limited only to a articular space vehicle may be avoided. In prior Air Force research on e human abilities necessary to fly aircraft in three dimensions, Fleischan and Hempel[25] note that many tests designed to duplicate what eemed important aspects of the pilot's job failed to achieve any predicon whatever. The problem, then, is to select mission tasks rooted in ound, well-defined human abilities of proved generality.

Task regime. Perhaps the most significant task the pilot can perform orbit is control of the attitude of his vehicle. In the event of failure of e automatic control system, he would have to undertake this task in rder that re-entry could be effected successfully by retrorocket firing. bout 20 per cent of his orbital fuel might be given over to the trimming cabin attitude by the pilot himself, leaving ample fuel for automatic ontrol.

A second task is the measurement of altitude. This is accomplished b the measurement of the earth's diameter in the field of a periscope fitte with a wide-angle lens. Several such measurements made during the firs and second orbits may establish clearly whether it is circular or elliptic long before ground-tracking stations can determine it. The precision this task should be at least great enough to tell the pilot whether he is i serious trouble, whether an unprogrammed re-entry is imminent. Alte nately, the diameter of the earth could be evaluated with infrared horizo sensors.

A third task is the determination of the pilot's position over the eart After the pilot has satisfied himself that he is safely in orbit and that hi attitude is appropriate for re-entry, he takes further steps to prepare fo an emergency. This activity is not unlike that of a pilot of any aircra who keeps in mind a field for a possible forced landing. Should some pa of his life support system fail, he may have to re-enter immediately t survive, regardless of ground recovery facilities at the point of impact Perhaps he may have enough time to choose a point of re-entry that wil bring him into an area well covered by air-sea rescue support. At leas once in each orbit a position will occur where there is maximum coverag for rescue. On any orbit, in the event of emergency, there will perhaps b one best time to initiate the re-entry sequence. By measurements of position and time (navigation) at two points, he can compute the best time for re-entry.

A matrix may be constructed which displays the assigned tasks and the primary abilities sampled (TABLE 4). The attitude control task, for instance, samples spatial orientation, response orientation, and contro precision. Altitude and orbit determination sample numerical facility an deductive reasoning. A discrepancy between the pilot's performance o these two tasks and that of his own prior performance leads to furthe analyses to determine which of the five primary abilities sampled i affected. In the case of navigation, the primary human abilities involve are chiefly spatial orientation and numerical facility, both of which hav been included before, but not together. Of the two, only spatial orientatio is present in the attitude control task, and only numerical facility in the altitude measurement task. If a primary ability is affected, it can b isolated by the study of weakness in the performance of tasks in which i is represented.

In the matrix, pertinent primary abilities are listed vertically and tasks are arranged horizontally. Among the tasks are samples of hue and brightness discrimination by visual observation of ground lights and reactio time, as well as tests of vigilance. One item of recurring interest i connection with space flight is the problem of how movements can b made and objects manipulated under conditions of no apparent weight.

TABLE 4

TASKS – PRIMARY ABILITY MATRIX

Ability	*Observation*	*Altitude measurement*	*Navigation*	*Attitude control*	*Monitoring*	*Maintenance*	*Math problem solution*
Intensity discrimination	X						
Color discrimination	X						
Vigilance					X		
Spatial orientation			X	X			
Numerical facility		X	X				
Mass judgment						X	
General reasoning							X
Deductive reasoning		X					
Response orientation				X			
Control precision				X			
Manual dexterity						X	
Memory			X				X

For instance, can the pilot in the weightless state determine the diffe ences between masses of objects with the same order of discriminatio that he can determine the differences between weights? To answer thi question may require a departure from the requirement of plausibility tasks. Sample rank ordering of masses may be used. Other tasks beari upon this problem and that of in-flight maintenance should include suc operations as manipulating tools and removing and replacing set screw Some methods of carrying out the task regime are shown in TABLE 5.

Intimately related to the performance of a task regime in orbit is th instrument display. In FIGURES 14 and 15 is shown a panel design spl in two parts to allow the pilot ready access to his seat and some capabi ity for moving around his vehicle in orbit (see frontispiece). The face the panel makes use of the latest recommendations of the Air Force an the Hughes improved cockpit display and control studies. These display have a number of advantages. Spatial information is given in an undistorted spatial analogue; accordingly, there is a minimum requirement t depend on numbers. Both the desired and the actual performance are fre to move against a fixed background: a pursuit rather than a compensato task. The direction of movement of the vehicle index is compatible wit the direction of movement of the craft itself in each coordinate, and th spatial displays present as much of the total situation as is consisten with scale-factor requirements.

If the orbital tasks are to be meaningful, serious consideration shoul be given to the establishment of performance base lines by extensiv controlled ground training in simulators. The Project Mercury pilots hav been selected from a specialized population consisting of engineer tes pilots. According to press reports, they display considerable homogeneit in general training background and physical condition. Data concernin their homogeneity in primary basic abilities are not known. If a tas regime is to be adopted, it remains to train the space pilots not only t the environmental and psychological stresses to be encountered, but t the task regime itself in order that homogeneity of performance be obtained. Under these conditions of homogeneity, the performance of eac man in orbit and on the ground should prove comparable to that of hi fellow pilots. The extent to which the simulator duplicates the structur and dynamics of the space vehicle will determine, in large measure, th degree to which the experimental tasks can be compared under the tw conditions.

Safety and Reliability

No system, regardless of its simplicity or redundancy, will work 100 pe cent of the time. Reliability is never absolute either in degree or time

us, failure of manned space vehicle systems will occur in the course
development of this technology. At this early stage, when experience
th the design and construction of environmental support systems for
n in space is limited almost entirely to capsules used for high-altitude
lloon flights, the risk of the venture is quite apparent. The question
ses: at what level does the risk become acceptable?

Reliability can be established only by a test program involving the
mponents of the system. Individual components must be qualified under
vironmental stresses such as acceleration, shock and vibration, and
mperature. Tests employing single environmental stresses should be
pplemented with operational tests under combined environmental
resses. Subsystems must be qualified in a similar manner. Finally, the
tire system must be tested. Although space cabins for orbital use have
en designed, they have yet to be fabricated in numbers and tested to
ilure. Many components for proposed manned space vehicle systems
ve been qualified, and some have been tested in ballistic missile
ghts. The ballistic-missile nose cone is an ideal test bed for the study
critical life-support hardware under the combined environmental
resses of actual flight.

The problem of sealed-cabin reliability has been discussed by
necci,[26] whose analysis, based on present avionic equipment reliabil-
, indicates that equipment with a mean time of failure of 100 hours can
oduce an acceptable 78.7 per cent reliability for a one-day orbital flight.
the duration of the space flight were extended to 10 days, using the
me equipment, a reliability of 9 per cent would be obtained. Depending
on the procedure during count down, the possible occurrence of holds,
d whether capsule function is required following re-entry and landing, a
tal mission duration of 48 hours, including 24 hours in orbit, is contem-
ated. To this must be added the time for operational assurance testing
d shakedown. It appears desirable that the present mean time of failure
lue should be raised at least by a factor of 10 for early flights and to
en greater values for longer flights. Increases in equipment reliability
st take place without an increase in weight. By careful engineering
dies and an extended qualification program, and by the accumulation
failure records, marginal equipments may be eliminated from the space-
bin system.

The National Aeronautics and Space Agency has proposed an extensive
ries of tests for the entire manned capsule system. These tests will
clude drop testing and short down-range shots, followed by longer bal-
tic trajectories. Subsequently the capsule will be placed in orbit for
e revolution. Finally, multiple orbits will be attempted. Many of these
sts will contain animal subjects, and a number may contain men. The
aluation of the reliability of the capsule will depend then on the con-

TABLE 5

TASK REGIME FOR MANNED SPACE FLIGHT

Basic abilities	*Mission tasks*	*Method of task performance*	*Type of response*	*Measure*
Intensity discrimination	Observation	Judge intensity of ground lights	Verbal	Known light intensities which can be seen from a position in space
Color discrimination	Observation	Judge color of ground lights	Verbal	Known colors which can be seen from a position in space
Vigilance	Monitoring	Oxygen supply indication; calculate remaining supply	Key punch; verbal	Frequency of pattern of monitoring; display reading errors
Spatial orientation	Navigation attitude control	Make position fix; record time and place; calculate re-entry point	Key code; verbal; written	Detection and identification of objects; rate of response; response error; changes in ability to make voluntary movements
Numerical facility	Altitude measurement navigation	Estimate altitude from angle measurement; make position fix; calculate re-entry point	Verbal; written; key code	Display reading errors in calculation; detection and identification of display error; judgment of position; ability to make error corrections

TABLE 5
(Continued)

Basic abilities	*Mission tasks*	*Method of task performance*	*Type of response*	*Measure*
Mass judgment	Maintenance	Set screws of several masses	Time; verbal; written	Ability to make manipulative responses; mass judgment errors
Deductive reasoning	Altitude measurement	Estimate altitude; predict re-entry; calculate apogee and perigee	Verbal; written	Display reading errors; errors in calculation; errors in deductive reasoning
Response orientation	Attitude control	Maintain straight and level flight	Telemetered data of position of vehicle	Errors in fine corrective movement; relationships of errors with time; judgment of position
Control precision	Attitude control	Maintain straight and level flight	Telemetered data of control correction	Errors in fine corrective movement; relationships of errors with time; judgment of position
Manual dexterity	Maintenance	Transfer set screws	Time; verbal	Time for manipulative movements
Memory	Navigation	Make position fix; record time and place; calculate re-entry point	Verbal	Detection and identification of objects; rate of response; response error; errors in calculation

tinuous interpretation of test data. What degree of success will required in tests before man goes aboard the vehicle is not yet decid The final evaluation of the acceptability of risk will be a complex de sion involving all parties: engineers, physiologists, psychologists, a the pilot.

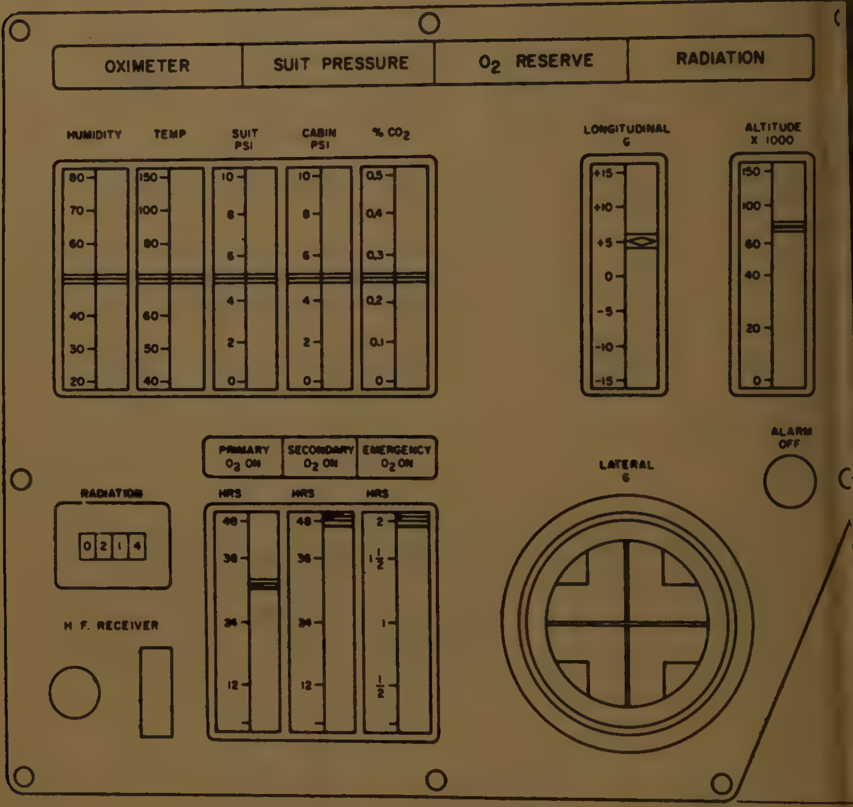

FIGURE 14. Split panel display *(left)*.

In the past, the occurrence of human error in aerodynamic flight ha contributed substantially to the accident record. The presence of the m in the space vehicle, however, may enhance its reliability greatly. T pilot's capacity for repair and maintenance and his ability to take ov manual control of automatic equipment may provide the required marg for success. Thus, an extensive training program of the astronaut required. Because of the presence of the man, the space vehicle syste is penalized by the requirement for emergency escape mechanisms. In t event of malfunction of the booster system on the launch pad accessor rockets will be required to fire the capsule free of the launch area and a sufficient altitude so that the parachute system can be utilized. T h fluctuating accelerations associated with booster failure during vered flight have been discussed. In this case, re-entry occurs where quate search and rescue facilities exist. In orbit there is no escape ept re-entry, irrespective of rescue facilities.

uccessful launch, orbiting, and re-entry will not constitute a success- flight unless the space vehicle is located and recovered. Considerable rt has been spent on the development of electronic aids for the recov- of nose cones, and technology in this area is well advanced. Air-sea cue procedures including aircraft search patterns and ship stationing st be integrated with predicted dispersion data. In this critical phase the mission, renewed attention is merited by the problems of visual s such as colors, sea markers, lights, and daisy flares. For example, high visibility of fluorescin dyes, commonly used as sea markers, is dually lost with time as the dye goes into solution in the sea, while visibility of aluminum slicks varies, depending upon the angle of the with respect to the viewer. In the latter case, with the sun behind the

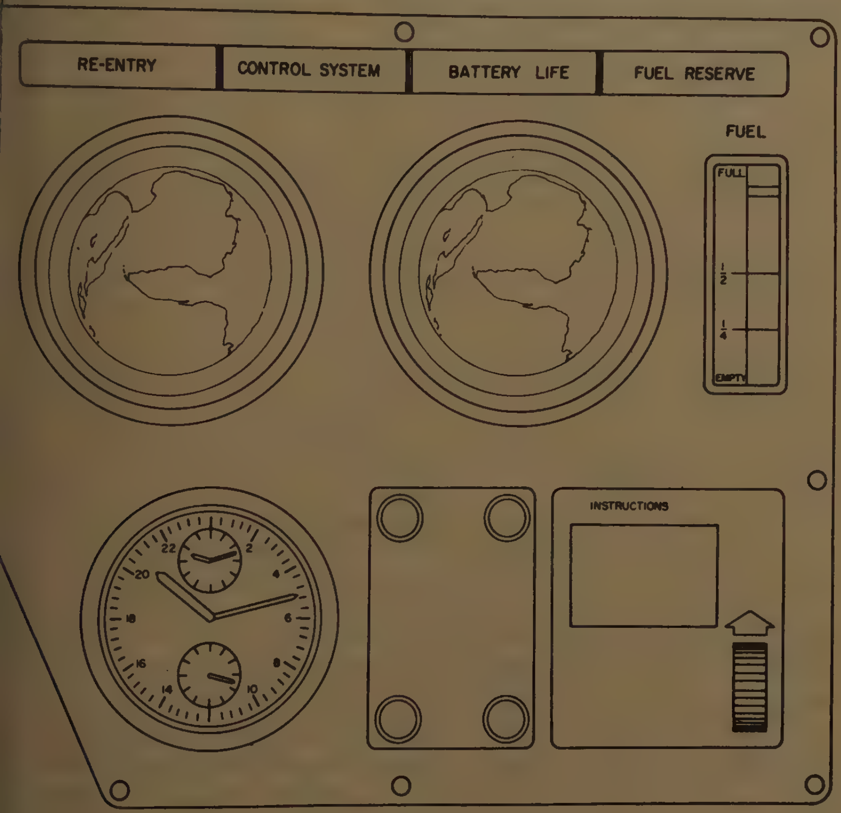

FIGURE 15. Split panel display *(right)*.

TABLE 6

SEALED CABIN RELIABILITY*

Operating time (t)		*Mean time of failure (T)*	*Per cent reliabili*
Days	*Hours*	*(Hours)*	$(\%R = e^{-t/T} \times 10$
1	24	10	9.0
		33	48.7
		100	78.7
		1000	97.6
10	240	100	9.0
		333	48.7
		1,000	78.7
		10,000	97.6
100	2,400	1,000	9.0
		3,330	48.7
		10,000	78.7
		100,000	97.6
1000	24,000	10,000	9.0
		33,300	48.7
		100,000	78.7
		1,000,000	97.6

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viewer, from the air an aluminum slick may be mistaken for a cloud. Wi the sun in front of the viewer, the reflection of the aluminum is high conspicuous in the open sea.

In addition to the problems of electronic and visual search aids, the are problems associated with the viewer himself. Studies are required the criteria for selection and training of searchers and of the relation vigilance and degradation of detection performance as a function of tim and field observations are needed in relation to such questions as clo covering and haze as they relate to intermittence and attenuation of visual stimulus. Ultimately it will take a man to find and recover the fir astronaut.

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